Local dark energy:

HST evidence from the expansion flow around Cen A/M83 galaxy group

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A structure with a massive group in its center and a cool expansion outflow outside is studied around the Cen A galaxy with the use of the Hubble Space Telescope observations. It is demonstrated that the dynamics of the flow is dominated by the antigravity of the dark energy background. The density of dark energy in the cell is estimated to be near the global cosmological density. This agrees with our previous result from the neighborhood of the Local group. A notion of the "Hubble cell" is introduced as a building block of the local structure of the universe.

Keywords: Groups of galaxies; the Hubble flow; Dark energy

1 Introduction

The Hubble flow of expansion is a natural tool to probe and measure the energy content of the universe. As is well-known, dark energy first revealed itself in the Hubble magnitude versus redshift diagram as a weak extra dimming beyond that

expected of the light from the Type Ia supernovae [1,2] at large redshifts. The diagram for Ia supernovae showed that, at even larger redshifts, the effect decreases with its sign changing near $z_V \simeq 0.7$, so that a weak relative light enhancement beyond that expected is observed at $z > z_V$. This has reasonably been taken [1-6] as an indication that the global cosmological expansion was being decelerated by gravity at times earlier than $z = z_V$ and accelerated by antigravity at times later than $z = z_V$.

At the redshift $z_V \simeq 0.75 \pm 0.05$ and at the corresponding distance ~ 1000 Mpc, the antigravity of dark energy and the gravity of matter (baryons and dark matter) balance each other for a moment. The balance condition is $\rho_M(z_V) - 2\rho_V = 0$, where ρ_M is the matter density, ρ_V is the dark energy density. It is assumed hereafter that antigravity is described by the Einstein cosmological constant Λ, so that $\rho_V = \Lambda/(8\pi G) > 0$. According to this simple, straightforward and quite likely interpretation, dark energy is the energy of the vacuum with the equation of state $p_V = -\rho_V$ [7]. Here p_V is the dark energy pressure, G is the gravitational constant and the speed of light $c = 1$. It is also taken into account that the effective gravitating density of dark energy (in General Relativity) is $\rho_V + 3p_V = -2\rho_V < 0$.

Since matter density scales with redshift as $(1+z)^3$ and the present-day matter density is known, $\rho_M(z=0) \simeq 0.3 \times 10^{-29}$ g cm^{-3}, the estimate of the dark energy density comes from Eq. (1), if the redshift value z_V is found in observations:

$$\rho_V = \frac{1}{2}\rho_M(z=0)(1+z_V)^3 \simeq (0.75 \pm 0.05) \times 10^{-29} g/cm^3. \qquad (1)$$

This figure has later been confirmed by the CMB anisotropy studies with WMAP observations [8,9].

A rather similar procedure enabled us to detect dark energy on relatively small spatial scales and estimate its density from the distance-redshift diagram for the local expansion flow in our close galactic neighborhood [10-13]. High accuracy observations of the local galaxies' flow with the Hubble Space Telescope [14-28] were used to discover local antigravity and estimate the dark energy density at a

few Mpc from the Milky Way. The local density of dark energy proved to be near, if not exactly equal to, the global figure of Eq.1. This result is independent of, compatible with, and complementary to large-distance observations.

In this paper, we report on the study of the local outflow around the galaxy group known as the Cen A/M83 complex. The data on the complex and its vicinity are used which have come from original observations with the Hubble Space Telescope [29]. Local dark energy effects are in the focus of the study. We demonstrate that the dynamical structure of the flow is significantly affected by the antigravity of the dark energy background. The local density of dark energy is estimated to be near the global cosmological density, or exactly equal to it. In Sec.2, the notion of the Hubble cell is introduced and theory considerations are outlined about local flows of expansion dominated by dark energy; in Sec.3, the basic data on the outflow around the galaxy complex Cen A/M83 are presented and analyzed; in Sec.4 the results are summarized.

2 Local expansion and dark energy

It has been mentioned long ago [30] and confirmed by the recent studies [31-33] that the Local Group of galaxies is archetypical for galactic systems on the spatial scale of ~ 1 Mpc. The group is dominated by the Milky Way and M31 located at about 0.7 Mpc from each other and moving toward each other with a relative velocity ~ 100 km/s. Other members of the group are the Magellanic Clouds, the Triangulum galaxy and about four dozen other dwarf galaxies. The group is $\simeq 1.5$ Mpc across and its total mass is $M = 1.3 \pm 0.3 \times 10^{12} M_{\odot}$ [25-28].

In the vicinity of the group, a two dozen galaxies move apart of the group and form the local flow of expansion discovered by Hubble in 1929. The flow is rather regular: it follows closely the linear velocity-distance relation known as the Hubble law. The rate of expansion (the local Hubble factor)is $H_{LG} = 72 \pm 6$ km/s/Mpc

[25-28], which is almost exactly equal to the global expansion rate measured by WMAP observations [8,9] and close to the expansion rate determined on the scale interval of 4-200 Mpc [34-36]. The flow is 'cool', and its velocity dispersion is less than 20 km/s [25-28].

These data have been obtained in systematic observations of distances and motions near the Local Group carried out over the last eight years with the Hubble Space Telescope during more than 200 orbital periods [14-28]. High precision measurements were made of the radial velocities (with 1-2 km/s accuracy) and distances (8-10 % accuracy) for about 200 galaxies of the Local Group and neighbors from 0 to 7 Mpc from the group center. The 6-m BTA of SAO and the Nordic Optical Telescope were also used, as well as results from the KLUN-project [37-42].

The theory approach to the local flows of expansion developed by us [10-13, 43-48] assumes that the flow structure and evolution is controlled by the gravity of the central group and the antigravity of the dark energy background in which all the galaxies of the group and the flow are embedded.

Each galaxy of the flow is affected by the gravitational attraction of the Local Group. Considering only the most important dynamical factors, we may take the gravity field of the group as nearly centrally-symmetric and static (this is a good approximation to reality, as exact computer simulations prove [44-46]. Then, according to Newtonian gravity, a galaxy is given an acceleration

$$F_N = -GM/R^2, \tag{2}$$

at its distance R from the barycenter (which is the origin of our reference frame).

The local antigravity is produced by the dark energy of vacuum with the uniform local density $\bar{\rho}_V$. Then, according to the 'Einstein antigravity law', the dark energy produces acceleration

$$F_E = G2\bar{\rho}_V(\frac{4\pi}{3}R^3)/R^2 = \frac{8\pi}{3}G\bar{\rho}_V R, \tag{3}$$

where $-2\bar{\rho}_V$ is the local effective gravitating density of dark energy. For details see

[12]. Eqs.2,3 describe the force field in the terms of Newtonian mechanics; a General Relativity equivalent is given by the static Schwarzschild-de Sitter space-time [12].

It is seen from Eqs.2 and 3 that the gravitational force ($\propto 1/R^2$) dominates over the antigravity force ($\propto R$) at small distances where the acceleration is negative. At large distances, antigravity dominates, and the acceleration is positive. Gravity and antigravity balance each other, so the acceleration is zero, at the "zero-gravity surface" which has a radius

$$R_V = (\frac{3}{8\pi} M/\bar{\rho}_V)^{1/3}. \tag{4}$$

The zero-gravity surface remains practically unchanged since the formation of the Local group some 10-12 Gyr ago, as the computer simulations [44-46] indicate.

The zero-gravity radius is a local spatial counterpart of the "global" redshift z_V: both indicate the gravity-antigravity balance. However, there is a significant difference between the global Friedmann theory and the local theory of Eqs.2-4. Indeed, the global gravity field is uniform and time-dependent, while the local field is non-uniform and static. Globally, the gravity-antigravity balance takes place only at one proper-time moment (at $z = z_V$) in the whole Universe. On the contrary, the local gravity-antigravity balance exists since the formation of the Local Group, but only at one distance ($R = R_V$).

The nearby expanding flow is made of dwarf galaxies. It is probable that the motions of these galaxies originate from the early days of the Local Group when its major and minor galaxies participated in violent non-linear dynamics with multiple collisions and mergers. Our theory and computer simulations [44-46] involve the concept of the "Little Bang" [49] as a model for the origin of the local expansion component. The model shows that some of the dwarf galaxies managed to escape from the gravitational potential well of the Local Group after having gained escape velocity from the non-stationary gravity field of the forming group.

When the escaped galaxies occur beyond the zero-gravity surface ($R > R_V$), their motion is controlled mainly by the dark energy antigravity and their trajectories

are nearly radial there [12, 44-46]. The trend of the dynamical evolution controlled by dark energy is seen from the fact that (as Eqs.2-4 show) at large enough distances where antigravity dominates over gravity almost completely, the velocities of the flow are accelerated and finally they grow with time exponentially: $V \propto \exp[H_V t]$. Because of this, the expansion flow acquires the linear velocity-distance relation asymptotically:

$$V \rightarrow H_V R. \tag{5}$$

Here the value

$$H_V = (\frac{8\pi G}{3}\bar{\rho}_V)^{1/2} \tag{6}$$

is the universal expansion rate which is constant and determined by the local dark energy density only [12].

If one assumes that the local density of dark energy is equal to the global figure of Eq.1, the value of the universal rate may be estimated as $H_V = 62 \pm 3$ km/s/Mpc. This is very close to the observed expansion rates at distances 1-3 Mpc and 4-200 Mpc (see above).

These considerations developed first in application to the close vicinity of the Milky Way can be generalized and extended to other local volumes on the spatial scale of a few Mpc. As we mentioned above, observations indicate that other small groups and their environment are similar to the local volume [30-33]. Computer identified groups from observational galaxy catalogs [50] have been shown to have an expanding population via a Doppler shift number asymmetry relative to the brightest member. In addition, large N-body ΛCDM cosmological simulations [51-56] show that such a structure is rather typical for scales of a few Mpc and more.

The structure with a massive galaxy group (or cluster) in its center and a cool expansion outflow outside dominated by dark energy seems to be a basic entity in the local structure of the universe. We will refer to it as a *Hubble cell*.

3 Cen A/M83 Hubble cell

The Hubble cell of Cen A/M81 contains the galaxy group which is called the Cen A/M83 complex [29] and the expansion outflow around it. This is the second nearest Hubble cell to the Local Hubble cell. A list of all known galaxies in a wide vicinity of a radius about 4 Mpc around the barycenter of the group contains 87 objects; 38 of them have no velocity or/and distance estimates. Most of the galaxies in the central volume of $\simeq 4$ Mpc across form two families – one, around the galaxy Cen A, includes mostly ellipticals and the other, around the galaxy M83, includes mostly spirals. The relative radial velocity of the centers of the two families is near zero. Their 3D separation is 1.3-2 Mpc.

The mass of the Cen A family (the central galaxy including) is estimated as $M_{CenA} \simeq (6-8) \times 10^{12} M_{\odot}$. The mass of the other family is about an order of magnitude less: $M_{M83} \simeq 1 \times 10^{12} M_{\odot}$. Thus, the total mass of the complex is practically the mass of the giant elliptical galaxy Cen A [29] and its surrounding.

Observational data [29] on the velocities and distances in the Cen A/M83 Hubble cell are presented in the Hubble diagram of Fig.1. The velocities and distances are given relative to the Cen A galaxy. The distances are determined with considerable errors which are shown in Fig.1 (without the error of the position of the central Cen A galaxy.) The accuracy of the distance determination is significantly lower there than in the Local Hubble cell where the error is typically about 10%.

The flow of expansion is clearly seen in Fig.1 at the distances 2-3 Mpc from the group barycenter (coincident with the position of the giant galaxy Cen A). The total number of the receding galaxies at the distances < 4 Mpc is 21. The flow reveals the linear velocity-distance relation (the Hubble law) with the expansion rate about 72 km/s/Mpc. The flow is cool enough: the velocity dispersion is about 30 km/s. As this value is affected significantly by the distance determination errors, the true value is still lower.

Using the general relation of Eq.4, one may estimate the zero-gravity radius for the Cen A/M83 group. With the mass of the group assumed as $M \simeq M_{CenA} = 7 \times 10^{12} M_{\odot}$ and the dark energy density $\rho_V = 0.75 \times 10^{-29} g/cm^3$, one finds: $R_V \simeq 2$ Mpc. According to the considerations of the section above, the members of the galaxy group (complex) must be located within the zero-gravity surface, and this is really so, as one can see from Fig.1. In particular, the galaxy M83, the second largest member of the group, is (most probably) located at the distance $R < R_V$. All the galaxies with negative velocities are also within the zero-gravity sphere. The considerations of Sec.2 indicate as well that the flow of expansion is expected to approach the linear velocity-distance relation outside the zero-gravity surface where the antigravity of the dark energy background dominates over the gravity of the group matter. Indeed, Fig.1 shows that this relation emerges starting from the distance $R \simeq R_V \simeq 2$ Mpc. All the galaxies at the distances $R > R_V$ move apart of the group; there is no infall (negative velocities) on the group at $R > R_V$.

The theory of Sec.2 makes a definite prediction: the expansion rate at distances $R > R_V$ must be near the universal expansion rate $H_V \simeq 62$ km/s/Mpc. The data above agree with this prediction within 15 % accuracy.

The theory makes also another specific prediction. It follows from Eqs.2-6 that at distances $R > R_V$, the velocities of the local expansion flow must be not less than a minimal velocity V_{esc} [12]:

$$V_{esc} = (\frac{2GM}{R_V})^{1/2} (\frac{R}{R_V})^{1/2} [1 + \frac{1}{2} (\frac{R}{R_V})^3 - \frac{3}{2} (\frac{R}{R_V})]^{1/2}. \quad (7)$$

The minimal velocity corresponds to the minimal total mechanical energy,

$$E_{esc} = -\frac{3}{2} \frac{GM}{R_V}, \quad (8)$$

needed for a particle to escape from the gravitational potential well of the group. Due to the antigravity of dark energy, this energy is negative. The velocity $V_{esc} = 0$ at $R = R_V$.

Actually, this prediction may serve as a critical test for the theory. In Fig.1, the minimal velocity V_{esc} is showed by a bold curve. The curve is determined by two parameters which are the group mass M and the dark energy density ρ_V; it is assumed in Fig.1 that $M = 7 \times 10^{12} M_{\odot}$ and the local dark energy density is equal the global dark energy density (see Eq.1). It is seen in the figure that all the galaxies at the distances $R > R_V$ obey this prediction: none of 21 galaxies of the flow at $R > R_V$ lies below the critical line. In this way, the data of Fig.1 indicate that the theory passes the test. It is even more important that the data are in agreement with the two basic parameters of the theory which are the group mass and the dark energy density. This means that the local density of dark energy in the Cen A/M83 Hubble cell is near or exactly equal to the global figure of Eq.1.

As in the case of the Local Hubble cell [12,13], one may follow the logic of the global determination of the dark energy density (see Sec.1) to estimate independently the value of the local dark energy density in the Cen A/M83 Hubble cell. For this goal, one needs first to determine the zero-gravity radius R_V. Basing on the theory considerations of Sec.2, one may robustly restrict the value of R_V with the use of the diagram of Fig.1. Indeed, since the zero-gravity surface lies outside the group (complex) volume, it should be that $R_V > 2$ Mpc. On the other hand, the fact that the linear velocity-distance relation is seen from a distance of about, say, 3 Mpc suggests that $R_V < 3$ Mpc. If so, Eq.4 leads directly to the robust upper (from $R > 2$ Mpc) and lower ($R < 3$ Mpc) limits to the local dark energy density:

$$(0.1 \pm 0.1) < \rho_V < (1 \pm 0.1) \times 10^{-29} \ \ g/cm^3. \qquad (9)$$

(Here the measured value of the mass of the complex is also used.)

The lower limit in Eq.9 is most significant. It means that the dark energy does exist in the Hubble cell. In combination, both limits imply that the value of the local dark energy density is near the value of the global dark energy density, or may be exactly equal to it.

In addition, the structure of the flow follows the trend of the minimal velocity: the linear regression line of the flow (the thin line in Fig.1) is nearly parallel to the minimal velocity curve, at $R > R_V$. It may easily be seen from the theory of Sec.2 that in the limit of large distances, the minimal velocity and the real velocity of the flow galaxies have a common asymptotics, $V \propto V_{esc} \propto H_V R$, independently on the initial conditions of the galaxy motion.

For a comparison, a similar minimal escape velocity, $(\frac{2GM}{R_V})^{1/2}(\frac{R}{R_V})^{1/2}$ is showed in Fig.1 for a "no-vacuum model" with zero dark energy density (dashed line). The real flow is obviously ignores the trend of the minimal velocity in this case: the velocities of the flow grow with distance, while the minimal velocity decreases. It is seen also that 19 galaxies of the flow at $R > R_V$ violate obviously the no-vacuum model: they are located below the dashed line. This comparison is clearly in favor of the vacuum model and against the model with no dark energy.

4 Conclusions

The Hubble cell is a notion in cosmology which appears with the new understanding of the local flows of expansion suggested in our works [10-13, 44-48]. The archetypical example of the Hubble cell is the Local cell which includes the Local Group and the cool expansion outflow around it. The major new physics discovered in the Hubble cell is the presence of dark energy and its domination in the dynamics of the expansion flows. The basic physical quantity which is characteristic for the cell is the zero-gravity radius R_V introduced in [10-13]. For the Local Hubble cell, $R_V = 1.2 \pm 0.1$ Mpc. The central group of the Hubble cell is located within the zero-gravity surface ($R < R_V$) and controlled mostly by the gravity of the group matter. The cool expansion outflow develops outside the surface ($R > R_V$), and its structure and evolution are determined by the antigravity of the dark energy background. The surface is nearly spherical and it is nearly unchanged for the

life-time of the Hubble cell.

A simple theory of the Hubble cell is based on the description of the gravity/antigravity interplay in terms of the Newtonian mecanics. The theory incorporates the concept of the Little Bang [49] according to which the expansion flow is formed by the dwarf galaxies that escape from the central group. The antigravity of the dark energy background makes the escape energy barrier lower, and in this way, it stimulates the process. The theory demonstrates that the major trend of the flow dynamical evolution is the development from chaos to order under the action of the antigravity of the perfectly uniform dark energy background. The initially chaotic ensemble of the trajectories of the escaped members of the group gains a regular structure in the phase space of the cell: 1) the trajectories tend to the linear velocity-distance relation; 2) they also tend to the universal expansion rate $H_V \simeq 62$ km/s/Mpc which is determined by the dark energy density alone and 3) the velocity dispersion in the flow decreases with time due to "vacuum cooling" which is much more effective than the adiabatic cooling. This evolutionary trend means that the Hubble cell are stable structures – any changes in their dynamics and kinematics lead only to a higher degree of order and regularity in them.

The Cen A/M83 Hubble cell ($R_V \simeq 2$ Mpc) studied in the present paper is a close analogue of the Local Hubble cell. The mass of this cell is considerably larger, and the mass is mainly associated with the central giant galaxy Cen A. Because of this, the approximation of the static spherical symmetry works in this case even better than in the case of the Local Hubble cell. The third example of the Hubble cell is the M81 galaxy group with its expansion outflow [57]. The gravity of this cell is dominated by the giant galaxy M81 (its mass is near the mass of the Local Group and $R_V \simeq 1.2$ Mpc), and so the theory approximation above is practically exact in this case. On a larger scale, the Virgo cluster and the Coma cluster with the expansion outflows around each of them ($R_V \simeq 8$ and 15 Mpc, respectively) may be treated as Hubble cells which extend to the distances $simeq 15$ and 30 Mpc.

Hubble cells acquire a role of the building blocks of the local universe. A world wide network of the Hubble cells may cover the observed space almost entirely. As a result, the structure of the universe within the cosmic cell of uniformity (scales less than 100-300 Mpc) proves to be more regular and better organized than it may be seen at the first glance. Indeed, the Hubble cells of various scales are all well ordered kinematically. Their zero-gravity surfaces are almost spherical with their radii almost constant in time during the last 10-12 Gyr. The overall dark energy domination makes the universe almost uniform on the scales exceeding the sizes of the zero-gravity radii which are 1-10 Mpc. On the same scales, the expansion rate is near the universal value H_V due to the dark energy dominance in the cell outflows. As is well known, the regularity of the quiet expansion flow – in spite of matter high irregularities – has been considered as a big mystery for decades [36, 58-60].

To conclude, modern cosmology emerged from the discovery of dark energy [1,2] is rich of new exciting implications that are due to the realization that dark energy rules not only the universe as a whole, but also our close galaxy environment [10-13]. The concept of the new type of astronomical objects – the Hubble cells – is one of these implications. These objects have a stable regular structure, they are omnipresent and introduce simplicity and order to the grand design of the universe on a wide range of spatial scales.

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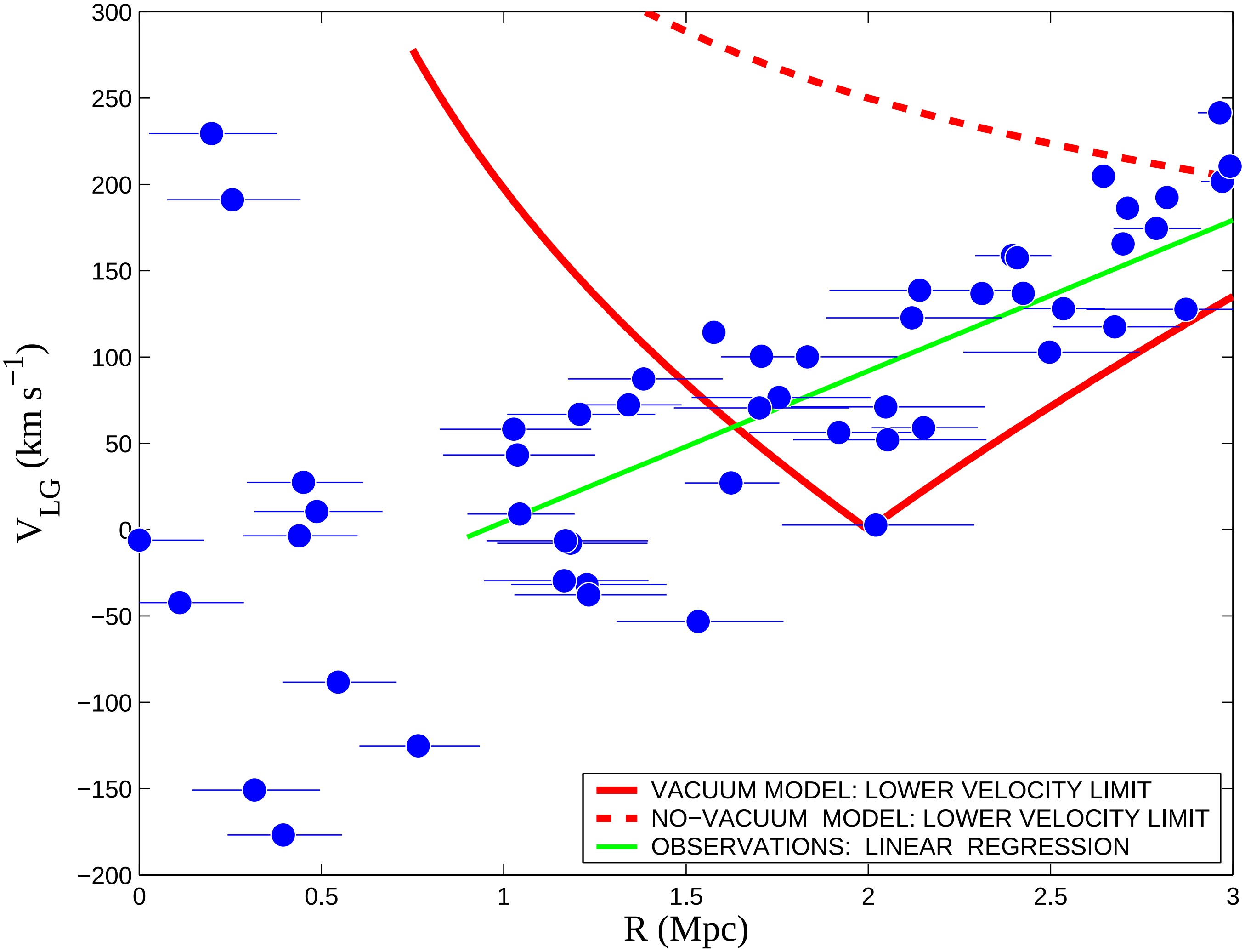

Рис. 1: The Hubble velocity-distance diagram for the Cen A/M83 Hubble cell based on the data [29]. The velocities and distances are given relative to the Cen A galaxy. The galaxies of the Cen A/M83 complex are located within the area of 4 Mpc across. The flow of expansion starts in the outskirts of the group; all the galaxies at distances $R > 2$ Mpc move apart of the group (positive velocities). The flow reveals the linear velocity-distance relation known as the Hubble law at $R \geq 2$ Mpc (see also the text).